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CORRELATIONS BETWEEN THE PULSE VELOCITY OF ULTRASOUNDS AND THE COMPRESSIVE STRENGTH OF CONCRETE IN STRUCTURAL ELEMENTS

F Giacomo, CNR, Istituto Centrale per l'Industrializzazione e la Tecnologia Edilizia, Italy

ABSTRACT

This paper describes the fundamentals of the theory of sound applied with the main objective of determining and measuring the velocity of ultrasonic impulses in concrete to establish an empirical relation between the velocity of propagation of the impulses and the compressive strength of concrete. The compressive strength of a standard concrete is established with tests on cylindrical specimens ($H/D = 2$) taken in-situ from beams, subsequently to the measure of velocity. The information previously available is used for the statistical analysis of regression and for the determination of the coefficient of correlation of distribution.

1. INTRODUCTION

The use of non destructive tests, in the determination of compressive strength of the concrete of precast concrete elements and structures, has in the ultrasonic method one of the main tools of investigation currently available; the application of the ultrasounds in fact, through the measure of the pulse velocity of propagation, is able to provide information on rapid-acquisition concrete which enables to establish an experimental correlation of pattern type, between the pulse velocity of propagation of the elastic waves and the compressive strength, that is fit to measure the quality of concrete and allows the comparative control in working conditions on the short and long term by examining just the ultrasonic datum.

The method of determination of the pulse velocity of ultrasounds propagation, developed essentially from 1935 on, owes its popularity above all to the evident existing comparison between the phenomena governing the propagation of the waves and the physical-mechanical properties of the medium in which these waves pass through. It is known, in fact, that the propagation of the elastic waves within a three-dimension homogeneous ideal isotropical medium, is obtained by formulating the study of the dynamic equilibrium of an elementary cube inside the body in order to achieve the formulation of the equations of motion [1].

The general integrals of two solutions of the equations of motion correspond to the existence about two types of waves that propagate in different ways, namely:

- the longitudinal or main waves (of traction-compression in which the displacement takes place along the direction of propagation of the same wave) with velocity of propagation V_p expressed by the relationship

$$V_p = \sqrt{\frac{(1 - \nu)E}{\rho (1 + \nu) (1 - 2 \nu)}}$$

the transversal waves or shear waves or secondary, (transversal motion as to the first in which the displacement lies in a normal plane as to the direction of propagation of the wave) with velocity of propagation V_s expressed from:

$$V_s = \sqrt{\frac{E}{2(1+\nu)\rho}}$$

where:

E = module of normal elasticity (N/ mm²)

ρ = density of the medium (Kg/ m³)

ν = module of Poisson

$V_{p/s}$ = main or secondary velocity (Km/ s)

It can be easily demonstrated that between the two relations, since ν changes really only between 0 and 1/2, the velocity of propagation of the longitudinal waves is greater than the transversal velocity and both velocities are independent from the frequency of vibration of the waves passing through the elastic medium.

In the case of one-dimensional bodies, where a dimension is prevailing as to the others (metallic bars, cylindrical sample with $H \gg D$) the motion of the longitudinal waves, when the wavelength λ is greater than the element thickness, can propagate in only one direction and, the effect due to the transversal contraction being negligible, the velocity of propagation of the longitudinal waves assumes the simplified formula:

$$V_p = \sqrt{\frac{E}{\rho}}$$

This velocity, if related to a concrete with module of Poisson conventionally assumed to be equal to $\nu = 0.24$ is a little bit different from what would be obtained by employing the first valid formula for the longitudinal waves in an three-dimension elastic medium, in fact, under the conditions supposed above for $\nu = 0.24$ the result is $V_{p(1)} = 0.921V_{p(3)}$, where the symbology assumes an obvious meaning. (1)

Beside the relations previously exposed, if the incidence of the shape of the body in the determination of the velocity of propagation of longitudinal waves V_p has to be appraised, it is necessary to refer to the link existing between V_p and the elastic characteristics in a two-dimension medium [2], under these conditions, for the same conventional reference concrete with module of Poisson $\nu = 0.24$, we have: $V_{p(1)} = 0.970V_{p(2)}$.

As regards the above mentioned considerations, that are obtained from the relationships existing between main pulse velocity of propagation and the elastic characteristics for one, two and three-dimension homogeneous isotropical mediums, they have induced some of the authors [3] to formulate for concrete elements, irrespective of their shape, a relation of the following type:

$$V_p^2 = K \frac{E}{\rho}$$

where K is a constant taking into account both the coefficient of Poisson ν of concrete and the element's shape; this constant can be assumed as being equal to 1.178. Such a relation has been assimilated by ASTM also in the standardization sphere.

The simplification introduced with respect to the theoretical approach and to the empirical links existing between the elastic module E_c and compressive strength R of concrete, suggests the possibility of deducing the latest directly from the ultrasonic datum, knowing at the same time that there is no functional univocal relation between the two variables, but that the relation between the velocity of propagation of the longitudinal waves and the compressive strength of concrete depends on many factors including age, maturation conditions, humidity conditions, the proportions of aggregates, the type of aggregate, the type of cement and the water/cement ratio used; if an estimate of strength is required, it will be necessary to establish a correlation between the compressive strength and the longitudinal velocity for the specific type of concrete under consideration.

This work aims at presenting an interpretative procedure for estimating the compressive strength by making use of the variable pulse velocity acquired from a particular type of concrete specifically formulated for remarkable structural uses.

2. METHODOLOGY AND TEST EQUIPMENT

Hereafter are briefly shown the test methodology and equipment necessary to achieve a complete non-destructive investigation through the use of ultrasonic waves in an range of frequencies having as lower extreme the frequency of 20 KHz, corresponding to the threshold limit of human perception of sound, while the upper extreme, for the investigations on the concrete, is set to 150 KHz, limit which is far lower than the field of frequencies normally employed for checking the defects of metal materials.

The measurement of propagation velocity of ultrasonic impulses generated from a electric acoustic transducer put in contact with one of the surfaces of the concrete element, is mainly based on the measurement of the time needed by the impulse to cross the mass of the sample under test and to reach the receiving probe; the electronically amplified signal is transformed into a temporal measure indicating the time needed by the impulse to cover the L distance which existing between the receiving probe and the transmitting probe. The velocity of propagation of the wave is calculated by dividing L by T. On the basis of the reciprocal position of the probes as to the geometry of the sample, it is possible to resort to mainly three techniques for the measurement of the velocity of propagation of ultrasounds, namely:

a) technique of direct transmission, otherwise known as transparency method; with this technique, the receiving and transmitting probes, are set on the opposite faces of the structural element under test in a position enabling to obtain the least distance between them; the test procedure is the most sensible because in such conditions, the transmitted waves are surely of the longitudinal type (waves of P type) and the transmitted signal suffers the least attenuation and a high percentage of the vibration is intercepted by the receiving probe;

b) semi-direct or diagonal transmission technique; it consists in applying the transducers on two adjacent faces of the element under test. Usually, the application of the probes is carried out by choosing two adjacent orthogonal planes belonging to the element to characterize; to this technique also belongs the direct configuration when the two probes are not diametrically opposed as to one another and the distance between the points of application of the probes is no more the least;

c) indirect or homeosuperficial transmission technique; both the probes are applied in different points on the same face of a plane surface delimiting the element to be tested. The efficiency of the method is notably reduced because of the uncertainty of the actual paths of the ultrasonic waves. The techniques indicated at points -a-, -b and -c have specific fields of application dependent from the type of control that is intended to be performed on the manufactured good or on the concrete sample and are subject to the structural restrictions and the geometric obligations imposed by the element to the particular realization of the envisaged test procedure.

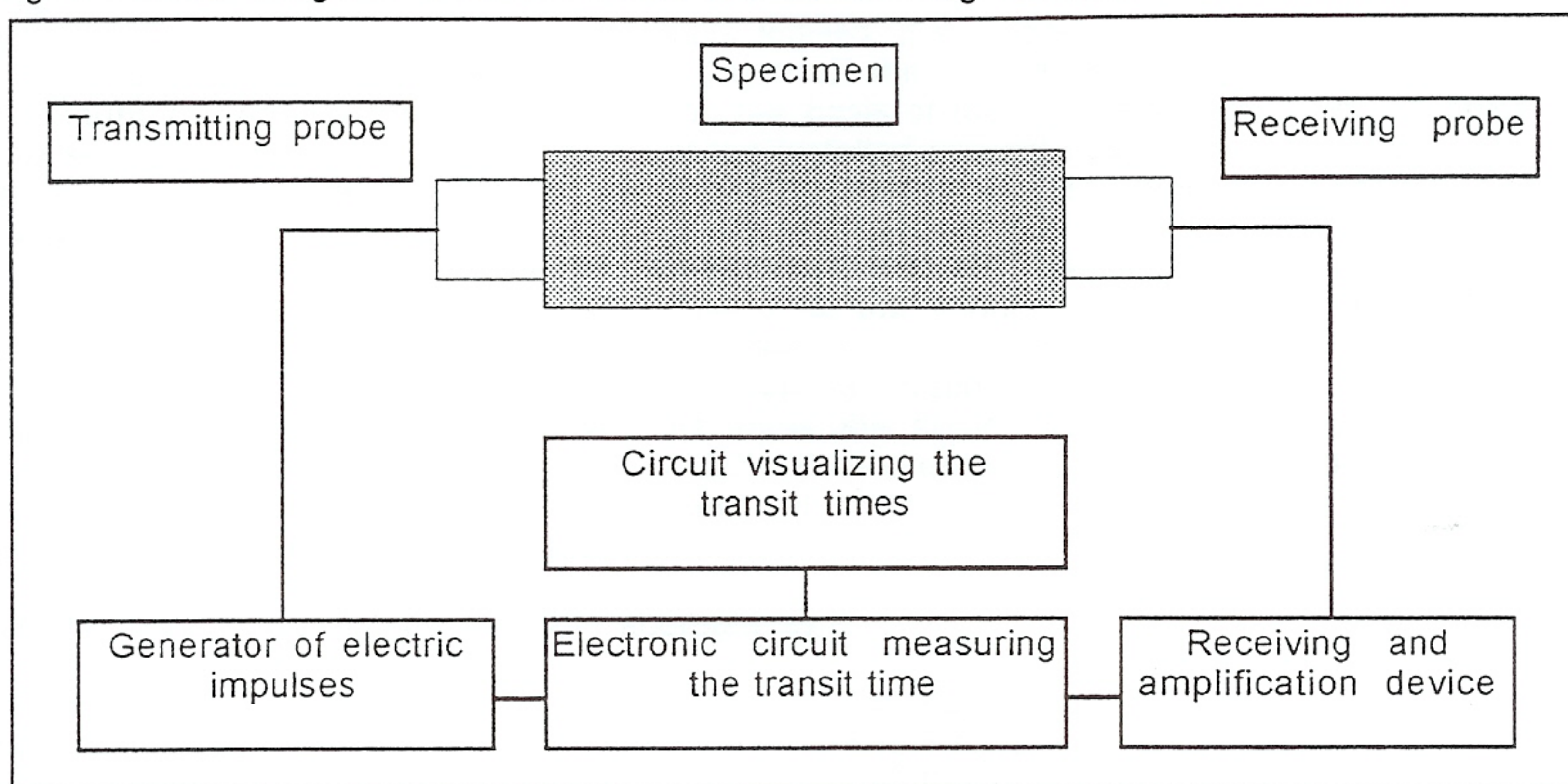
Each technique underlines different characteristics of transmission, as regards refraction and reflection phenomena of the ultrasonic waves incident on the surfaces delimiting the element under test placed in the surrounding environment acting as a separating medium, in a way to be more suitable for some particular rather than others; the more evident case is the indirect method, when it is used to determine the superficial quality of concrete in relation to the other inner layers or when it comes to determining the depth of a crack with normal position as to the surface of application of the probes.

In considering the three transmission techniques, the transparency system is the most sensitive, since the results obtained are the most representative of all the thicknesses of the examined concrete; in this work, since there are no other obstacles, the method for transparency has been used systematically for the measurement of propagation time through the samples of concrete specifically obtained for the experimentation.

The test apparatus used is schematically represented in [figure 1].; it essentially consists of the following functional units that are electrically connected:

- a- to a generator of electric impulses coupled with the relative probe of transmission of piezoelectric type which transforms the electric impulses produced by the generator into vibrations of known frequency. In the case of the equipment actually used, the nominal characteristic of vibration of the transducer resulted to have a frequency of 54 KHz;

Fig. 1- Block - diagram of an ultrasound tool for checking concrete



- b- to a receiving probe, similar to the former transmitting probe, that transforms the mechanical vibrations, intercepted by the surface in contact with the specimen, into electric signals to be sent to an amplification device in synchronism with the generator of impulses;
- c- to an electronic circuit measuring the transit time elapsed since the instant of emission of the impulse to the instant in which this reaches the receiving probe;
- d- to a circuit visualizing the elapsed times, normally provided with the available instruments on the market in two versions that are simultaneously active; the former consists essentially of an oscilloscope whose cathode-rays tube visualizes the transmitted and received wave, while on the time axis it is possible to measure the interval of time elapsed between the two signals; the latter, indicating the elapsed time, employs a digital timer with quartz oscillator; the device directly visualizes the temporal interval on a liquid-crystals display.

The selection of the field of frequencies within which lie the individual nominal values of the emitting probes, to be used on concrete in ultrasonic investigations, is made on the basis of energetic considerations relative to the attenuation of the ultrasonic wave' propagation motion through the medium; the distance that this could cover depends on the initial amplitude of the wave, on the frequency and on the nature of the medium. The attenuation of the acoustic pressure as a function of distance is exponential and occurs as rapidly as the frequency of the probe is great; this circumstance can be understood by bearing in mind that, the velocity in the medium being independent from the frequency as regards velocity itself, velocity must be considered as constant; therefore, from the relation $V = \lambda F$, it can be deduced that, the velocity of propagation in the medium being invariable, to high frequencies correspond short wavelengths, but in this case, for what concerns concrete, if λ is of the same order as the aggregates' diameter, the possibility of having an energy loss increases because there is a higher possibility that the wave diffuses in all directions. As regards concrete, this last circumstance limits the application of ultrasounds with frequencies greater than 150 KHz, because if frequencies of vibration greater than the fixed limit were reached, the wave would not be able to penetrate concrete and, following the great attenuation, it would be quickly dampened along the initial part of its path. The choice of the type of probe to be used in the following experimental campaign has derived from considerations on the path lengths to be investigated and from the nominal characteristics of frequency of the probes supplied by the producers of instruments for ultrasonic tests.

3. RESULTS OF THE EXPERIMENTATION

The experimental phase of this work has been carried out in the latter phase of the production process, on a series of pre-cast beams. As frequently happens whenever a non-destructive investigation is required, uncertainties had risen about the conformity of the

compressive strength class of the used concrete with respect to that prescribed during the design phase. Italian standards on the subject, with D.M. n. 19 of 9/1/96 currently in use, in enclosure 2 "Controls on concrete", point 5.3, "Prescriptions common to both control criteria" quote the following statement:

- if a prescription of the acceptance control is not fulfilled, it is necessary:
- to resort to a theoretical and/or experimental control of the security of the structure concerned by the amount of non-conforming concrete, on the basis of the reduced strength of concrete, that is to say, a control of the characteristics of the installed concrete by means of any available complementary tests, or by sampling some installed hardened concrete ([ie]. core borings) or by using other means of investigation.

The general character of the standard with reference to the means of investigation, allows to formulate the ultrasonic method as an alternative for the verification of the conformity of the characteristic cubic strength of concrete (R_{ck}) to the required design requirements.

In accordance with the standards referred to above, preliminary investigations concerning the design specifications of concrete elements under this sonic characterisation, lead in every case to consider the project characteristic compressive strength R_{ck} and the mix design of the used concrete. For what concerns the case under examination, the mixture used for the casting resulted to have the following composition:

Concrete for beams: (Weighing 1 m³ dry aggregates)

• Cement 425	350 Kg/ m ³
• Sand	850 Kg/ m ³
• fine aggregate	140 Kg/ m ³
• coarse aggregate	950 Kg/ m ³
• Super - fluidificant	0.8%
• Water/cement	0.45
• Slump	12 cm

It is necessary to report the fact that the following inevitable different beam's castings compacting as regards the corresponding sampled cubes and the uncontrolled variation of the water of mix, which is always possible, are the factors that more often affect the concrete strength subjecting it to variations that cannot always be checked and that therefore are accountable for a defective correspondence between the strength of the cubes and that of the concrete employed in the structural elements.

In order to prevent the restrictions previously indicated, a sampling of concrete used for creating an initial series of beams has been carried out by extracting a representative specimen of micro-cores collected directly from the produced structural elements. This sampling is essential to establish a calibration curve of the type $R = f(V)$ between the generic non-destructive parameter V of velocity and the strength of the installed concrete; it allowed for the creation of 38 cylindrical samples with nominal diameter $\phi = 5$ [cm] and height $H = 10$ [cm], obtained by cutting the reference micro-cores that were previously obtained having the same height as the thickness of the core of the beam to which they originally belonged. All the following laboratory tests have been carried out on samples aged for twenty-eight days in normal conditions of temperature and humidity.

These tests have focused on the determination of the mass per unit volume, of the ultrasonic waves' longitudinal velocity of propagation and concluded with the breaking of the samples for the evaluation of the cylindrical compressive strength [f_c].

4. STATISTICAL ANALYSIS OF THE EXPERIMENTAL RESULTS

The numerical values obtained with the experimentation have been subsequently treated through methods of statistical analysis according to distinct phases and to the different proposed scopes. In the first phase the three random variables, main velocity V_p , cylindrical compressive strength [f_c] and mass per unit volume ρ have been considered separately and, for each of the three samples extracted from the respective populations, the calculation of the most meaningful statistical indexes has been also carried out. In table 2 are reported the main parameters estimated on the samples obtained from the respective populations that are supposed to be distributed normally; for the individual random variables of mass per unit volume ρ , main velocity of propagation V_p and cylindrical compressive strength [f_c], the table reports the estimated values of mean, variance of the empirical standard deviation, coefficient of

variance intended as the percent ratio between the empirical standard deviation and the mean, of the characteristics values or fractiles in the region of 0.05 and shows the ranges of the samples extracted from the respective populations, by reporting the maximum and minimum values measured. As regards the results of more specific interest for what concerns the subsequent data processing through the analyses of correlation and of regression, for the random variables of main velocity V_p and of cylindrical compressive strength $[f_c]$, the respective histograms of frequency are developed, while for the same data the diagrams of distribution of the respective cumulative relative frequencies are obtained, where by relative cumulative frequency of each element of the sample we mean the ratio between the element's order number subsequent to the classification of the data in mounting progression and the corresponding dimension of the sample plus one unit.

	Volumic Mass Kg/m ³	Main Velocity m/s	Cylindrical strength N/mm ²
mean	2251	3850	32
variance	3005	10679	14,36
Empirical standard deviation	54,82	103,34	3,79
Coefficient of variance	2,43	2,68	11,69
Characteristic value in the region 0,05	2161	3680	26
maximum value	2363	4098	23
minimum value	2131	3681	43

Table 2- Statistical parameters relative to laboratory tests

The cumulative distribution curves are an approximate estimate of the functions of probability $P(R)$ and $P(V)$ of the respective random variables of velocity and cylindrical strength. The main consideration worth taking into account, following the comparison of the statistical parameters, is the remarkable difference of the C_v coefficient assumed from the cylindrical strength $[f_c]$ as regards the same parameter estimated on the other random variables of velocity and mass per unit volume of the statistical sample, but more in general as regards the values that are normally found in the determinations of cubic strength R_c on standardized cubes or of cylindrical strength on the standardized sample.

Such an effect consists of an increased variability of the cylindrical strength according to the variation of the sample's diameter, even when known [4] and explained by the theory of "addition of strength," according to which: "the standard deviation of the compressive strength decreases as the core's diameter increases and, by comparing two groups of cylindrical samples with different diameter the same value is obtained when the number of samples of the two groups is such that the addition of the areas of their section results to be equal"; however, such effect is not suitably integrated in the standards in force and it is incidentally dealt with in paragraph "Characteristics of hardened concrete" of CNR Instructions published in 1982.

The above considerations show that the only measurements of the cylindrical $[f_c]$ and characteristic strength $[f_{c,k}]$ obtained from tests of compression on micro-cores of diameter $\Phi = 5$ [cm], cannot be practically used to obtain the equivalent standardized values, because of the inapplicability of the factors of conversion between compressive strengths of cubes/cylinders and due to the lack of homologous indexes to be applied to the cylinders taking into account the diameter D and the slenderness of the sample H/D . Therefore the preceding analysis requires further types of statistical investigation making plain the research of the connection between the two random variables of cylindrical strength and longitudinal velocity, distributed in the plane V,R with density of probability $w = w(V,R)$ that is assumed to be normal. By giving up the development of the statistic of the two random variables V and R , and by just applying the calculation and the interpretation of the coefficient of correlation of Pearson:

$$r = \frac{\sum (R_i - \bar{R})(V_i - \bar{V})}{\sqrt{\sum (R_i - \bar{R})^2 \sum (V_i - \bar{V})^2}}$$

defined in a dimensionless way as the ratio between the co-variance and the outcome of the mean square deviations of the two random variables of main velocity and cylindrical strength; ratio, varying in the interval $-1-r-1$, calculated on the original specimen and on a fictitious specimen obtained from the couples (v_i, R_i) of data having the same cumulative relative

frequency in the respective diagrams of distribution previously established, that for the statistical specimens of the investigation has assumed the following values respectively:

$$r(\text{original}) = 0.194$$

$$r(\text{fictitious}) = 0.960$$

it is possible to make the following considerations also supported by similar results obtained in other experimentations [5]; having achieved the meaning of coefficient of linear correlation r , which could be considered as a measure of the linearity of the link between the variables of main velocity and cylindrical strength for $0 \leq r \leq 1$, (strictly linear for $r = 1$, no correlation for $r = 0$) and the meaning of direct positive correlation for $r > 0$, it is possible to draw the following conclusions: the correlation existing between main velocity and cylindrical strength is of positive or direct type; this implies that, statistically, the cylindrical strength increases with the increase of velocity.

Even if the result is valid from a quantitative point of view, it cannot be actually applied in real cases, unless it is referred to general conditions of concrete's quality level to be fixed from time to time on a specific concrete production, as shown by some authors [6] through a classification of the material of the following type:

very poor	$V < 2135 \text{ m/s}$
poor	$2135 - 3050 \text{ m/s}$
quite good	$3050 - 3660 \text{ m/s}$
good	$3660 - 4575 \text{ m/s}$
excellent	$V > 4575 \text{ m/s}$

obtained from an evaluation of the values of strength and velocity measured and averaged in a vast campaign of cognitive investigation.

The analysis of regression is the following step for the interpretation of the data acquired during the sampling phase. The method of regression is used in two-dimension distributions, when the scope is not adjusting a law of probability to the observations, but when it comes to establishing in an easy and practical way a statistical link between two random variables such as the main velocity and the cylindrical strength.

For the application of the method, it is necessary to choose some curves that suitably fit to the data, but since the variables are two, namely velocity and cylindrical strength, it will be necessary, first of all, to establish which of the two variables will take on, in the functional empirical link, the meaning of independent variable and which that of dependent variable, or, in other words, which type of regression (R on V) and curve of regression are to be adopted. The method implies presumptively the choice of the type of curve of regression; those adopted for the two checked statistical specimens are represented by the following families of functions:

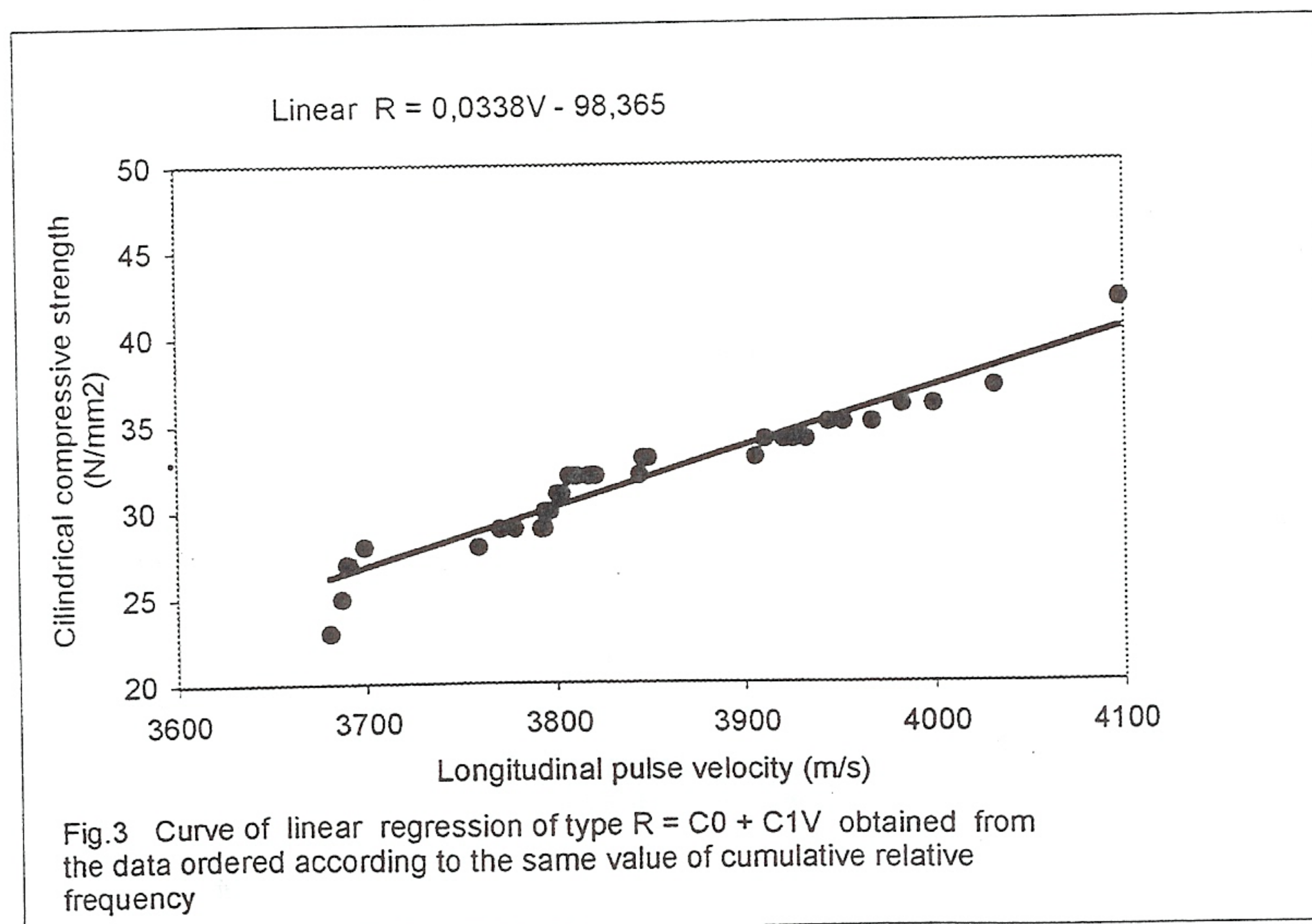
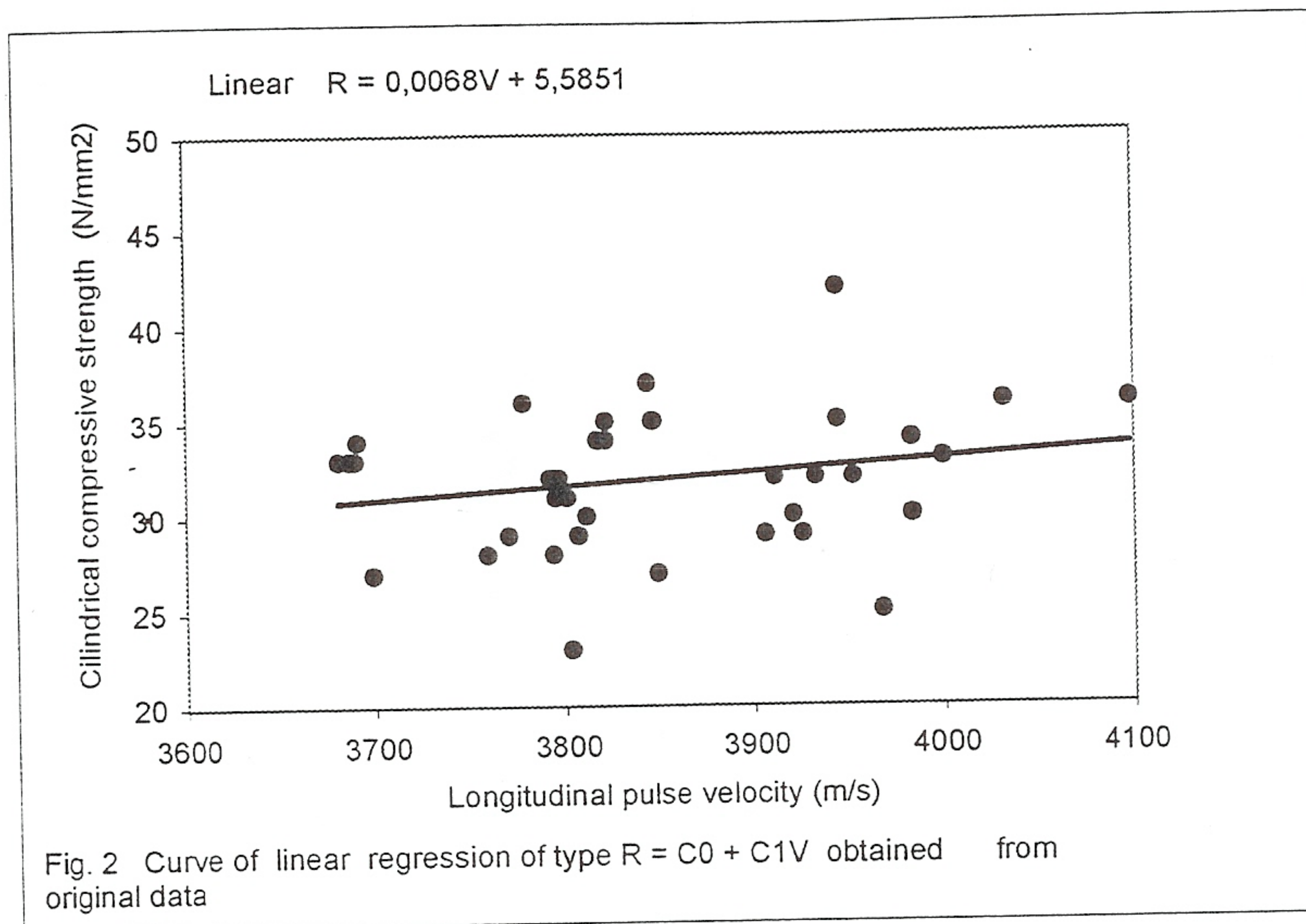
linear	$R = C_0 + C_1 V$
power	$R = C_0 V^{C_1}$

where R and V are the cylindrical strength and the main velocity respectively, while the individual coefficients C_0 and C_1 , of each curve, are to be determined for each of them, with the method of the lowest squares by minimizing the sum

$$S = \sum (R_i - R_{is})^2$$

of the squares of the deviations between the values of the variable cylindrical strength R_i and the corresponding R_{is} values that, the value of principal velocity V being the same, can be read on the curve of regression.

Once the C_0 , C_1 constants for the four curves have been calculated (they are analytically and graphically reported in figures 2 to 5), representative respectively of the statistical original specimen and of the fictitious one obtained from the data of velocity and strength, which are in turn ordered in a way to represent points (R_i, v_i) having the same value of cumulative relative frequency, the analysis has ended with the calculation of the main parameters for estimating the errors of measurement which are synthesized by the residual deviation, $[d_r] = \sqrt{\frac{1}{n} \sum (R_i - R_{is})^2}$, where R_i represents the ordinates of the experimental points and R_{is} the ordinates of the corresponding points estimated on the curve of regression, of the standard estimate error, defined as $s = \sqrt{[d_r] / (n - 2)}$ and, at last, of the coefficient of determination r^2 quadratic expression of the coefficient of correlation r ; all of these characteristics are reported in table 3.



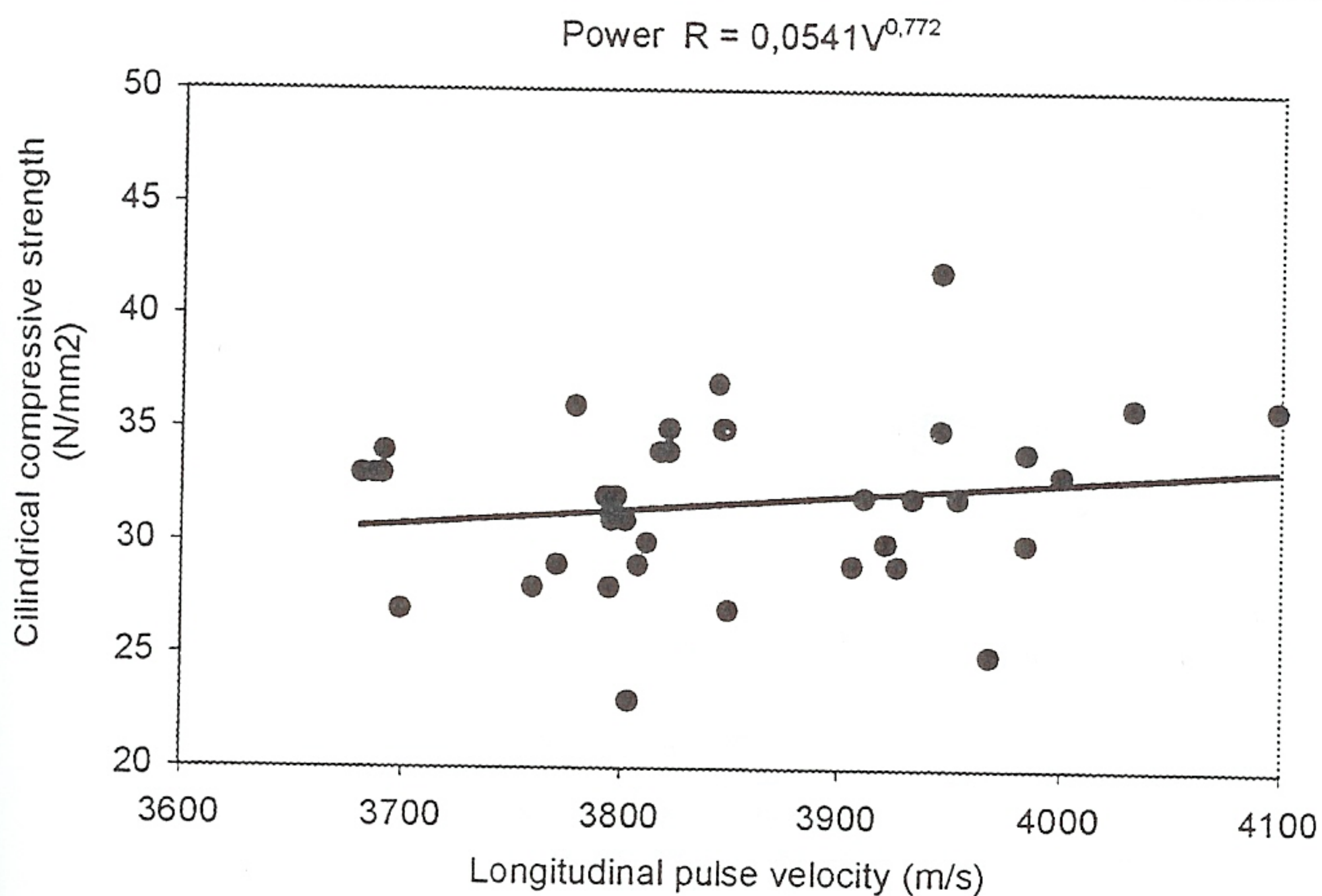


Fig. 4 Curve of regression of type $R = C_0 V^{C^1}$ obtained from original data

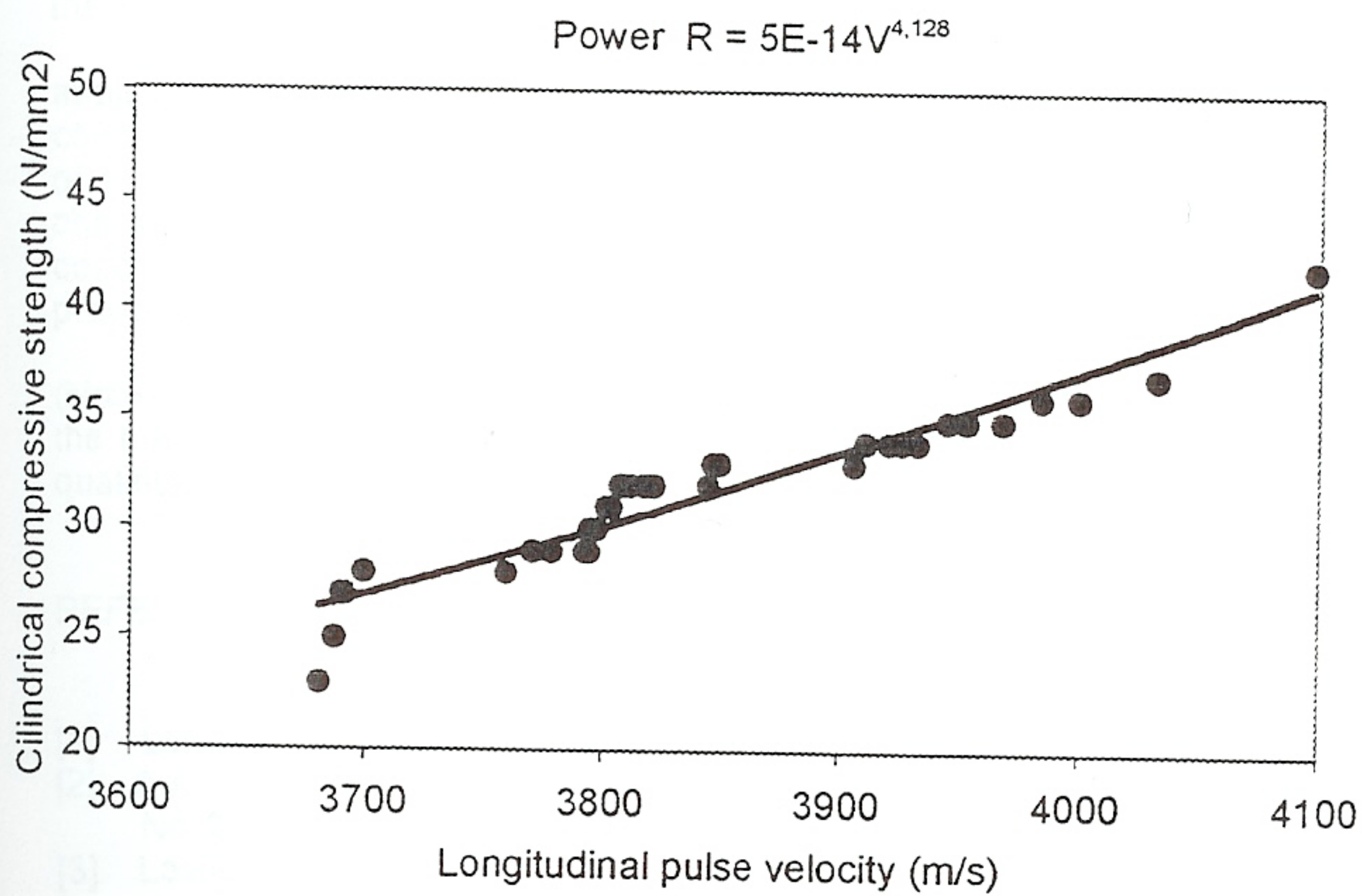


Fig.5 Curve of regression of type $R = C_0 V^{C^1}$ obtained from the data ordered according to the same value of cumulative relative frequency

	Type of function	Residual Deviation	Standard Error	Coefficient of determination
original specimen	Linear	457,38	3,564	0,038
	power	473,98	3,628	0,032
fictitious specimen	Linear	36,98	1,013	0,922
	power	42,00	1,080	0,901

Table 3- Statistical parameters of the analysis of regression.

5. CONCLUSIONS

In order to carry out a complete and correct analysis, also the confidence limits of coefficients C_0 and C_1 should be appraised; the formal exactness of the analysis would be limited if, first of all, the most suitable empirical relation for the interpretation of the available data, was not chosen, by resorting to a sampling investigation to be carried out by means of pulse velocity and cylindrical strength measurements.

In this respect, the available methods of interpretation [7] which are studied and employed mainly in Eastern Europe, foresee, after the adoption of a type of curve of regression for the standard reference concrete usually not linear and of type $R = C_0 V^{C_1}$ with $C_1 = 4$, the use of global coefficients of influence, to be established according to the composition of concrete, in order to go from strength values measured on standard concrete to strength values appraised for a generic modified concrete.

Coming back to the reasons that originated this work, about the actual use of the above mentioned empirical relations, for what concerns the production control of structural elements, it must be pointed out that these have attained the required forecasting reliability the ultrasonic control method used must ensure and that they have been confirmed by other similar results obtained with sclerometric tests carried out in parallel to the ultrasonic investigation; on the other hand, the previous remark does not apply to the standardized tests on cube, performed during the production phase of the beams, to ascertain any overestimation of strength due to the technological error occurred during the preparation of the cube.

The ultrasonic investigation is therefore proposed as a non-destructive test method applicable to concrete elements after the curve of specific calibration for the reference concrete has been traced. The method turns out to be interesting not only due to the possibility of foreseeing the strength on site, but also and mainly because it offers the possibility of characterizing the heterogeneities and the alterations that could be incurred into by the concrete over the time, which can be measured by means of the decrease of the velocity of propagation in the manufactured article.

(Note 1) The relations linking the ultrasounds velocity of propagation to the elastic constants of the medium, always refer to elastic modulus E and to coefficients of Poisson ν that are normally qualified as "dynamic", in order to specify the methods usually applied for their determination.

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